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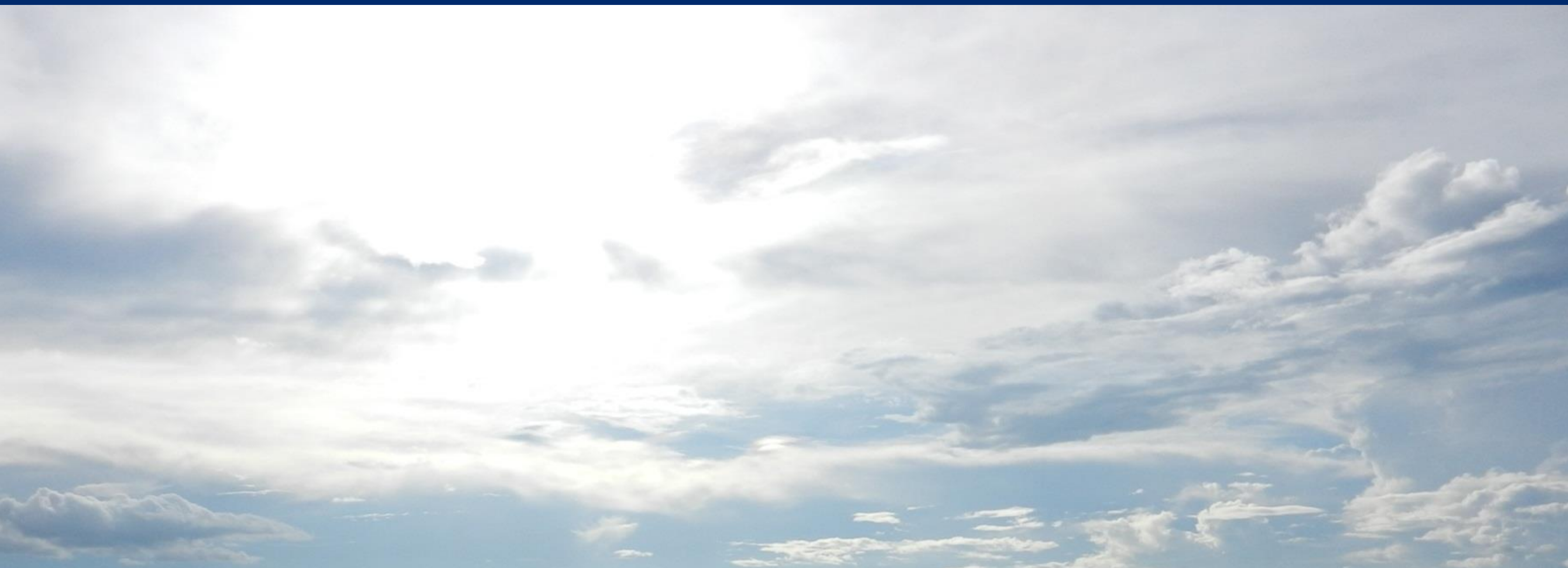
Anthropogenic Climate Change and Hydro-Climatic Conditions in the Cubango-Okavango River Basin



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ANTHROPOCENTRIC CLIMATE CHANGE AND HYDRO-CLIMATIC CONDITIONS IN THE CUBANGO-OKAVANGO RIVER BASIN

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INTRODUCTION AND BACKGROUND

Anthropogenic climate change

Anthropogenic climate change is a phenomenon currently accepted in the mainstream science as real and undisputable. This phenomenon is caused by emissions, from man-made sources, of greenhouse gases (GHG - carbon dioxide, methane and a number of others) and aerosols into the atmosphere. In brief, greenhouse gases and aerosols influence properties of the atmosphere through affecting the way radiative energy, particularly thermal radiation, passes through it. The change in concentrations of greenhouse gases and aerosols affects the energy balance of the Earth, leading to a net increase in air temperatures – the so-called greenhouse effect. This increase in air temperature has numerous consequences to the climate system – amongst others it causes an increase in water holding capacity of the air, which means that more water can be transported within the atmospheric circulation system. Also, it leads to an increase in ocean temperatures, which affects ocean currents, and because large-scale atmospheric circulation is strongly influenced by sea surface temperature patterns, that circulation is altered too. There are numerous other reverberations and feedbacks occurring in the climate system as a consequence of anthropogenic emissions of GHG, and all these have a potential to affect all aspects of weather, not just the temperature, at any location on the Earth.

Climate and weather at a location is a result of a complex interplay of many factors affecting external forcing (solar radiation reaching the earth surface), large (continental) scale atmospheric circulation (heat and moisture transport in the atmosphere, mainly driven by differences heat absorption between oceans and land), and modified by local scale processes and feedbacks (such as, for example an oasis effect, or topography-induced meso-scale and local weather patterns). The complexity of interactions of elements of the climate system leads to natural variability of weather conditions manifested at a number of time scales – from diurnal, to seasonal to interannual to multidecadal. Therefore, any effects of anthropogenic climate change have to be assessed against and distinguished from the natural climate variability.

Modelling of climate system and climate change

Global climate models

Global climate models (GCM) are tools commonly used in assessment and understanding of anthropogenic climate change. A GCM is a computer program in which processes of mass and energy transport in the Earth's climate system (atmosphere, oceans and land surface) are described using a set of mathematical equations. Such a model allows for simulation of the Earth's climate system, also under hypothetical conditions not observed earlier. This makes it useable for preparing projections of future climate under various scenarios of future greenhouse gas concentrations.

There are approximately 30 GCMs run at various climate-modelling centres around the world. These GCMs differ in spatial resolution, climate processes they represent, the way the processes such as regional mean and transient circulation, moist convection, land-atmosphere feedbacks and aerosol effects are represented and parameterized, and computational methods used to solve the underlying mathematical equations. Some processes such as land use change, variations in solar and volcanic activity and CH_4 release from permafrost or oceans, are not included in some GCMs. As a result, the models differ in results of their simulations. Importantly, it is currently considered that no GCM is the best, and that there is in principle no gradation of good and bad GCMs. This partly results from the fact that model gradation depends on the metric (e.g. models better in simulating temperature might fare worse in terms of rainfall, or pressure) and geographical scope (models better in simulating southern Africa might fare worse in terms of global conditions) etc. It is, therefore, a common practice to use all the GCMs outputs as an ensemble of viable possibilities. In this context, the multi-model ensemble spans the range of uncertainty related to the current state of knowledge on the workings of the climate system and on how to represent a climate system in a computer simulation.

Downscaling of GCM output

GCMs have a limited spatial resolution – i.e. they resolve features of Earth's climate that are typically larger than 150-300 km. Local climates are, however, influenced by processes (e.g. formation of convective systems) and features (e.g. topography and land cover) occurring at smaller scales. As a result, downscaling of GCM outputs is often needed in order to "translate" the GCM large-scale data into information appropriate to the scale at which climate is perceived. Importantly, the process of downscaling is different from the process of interpolation. While interpolation simply determines the value of a given variable at a point purely from the coarse original information, downscaling adds new information that reflects the influence of small-scale features on the variable of interest. There are two principal ways of downscaling GCM output: dynamical and statistical.

In the dynamical downscaling, a higher resolution (typically 25-50 km) climate model is run for the area of interest. This regional climate model (RCM) is "nested" in a GCM, i.e. it uses certain driving variables from the parent GCM. The RCM adds locally relevant information to the output, because it is able to better represent such factors affecting local climate as land cover, topography. Additionally, it is able to represent processes that are smaller than the resolution of a GCM, for example meso-scale convective systems. Although RCMs improve the representation of local climate, uncertainties of the RCM add to these arising in GCM simulations. Additionally, there are a number of different RCMs available and each of them can be nested in one of the available GCMs. This potentially generates a large number of possibly divergent simulations. A coordinated effort for systematic use of RCMs in downscaling has been initiated under the CORDEX project (http://wcrp.ipsl.jussieu.fr/SF_RCD_CORDEX.html), and data from this project are soon to be published on-line.

Statistical downscaling relies on ground observations to develop a statistical relationship between large-scale variables simulated by a GCM and the local scale weather. That empirical relationship implicitly reflects the influence of local conditions on the local weather. Statistical downscaling is conditional on the observations, i.e. it cannot be performed for locations for which adequate observations are not available, and similarly to RCM, there are method-to-method differences and uncertainties in GCMs propagate into the final output. A coordinated effort to systematize statistical downscaling activities is also a part of the CORDEX project with results forthcoming in the near future.

Uncertainties of climate change projections

The nature of the models themselves, as well as the context in which they are used (predicting future of a complex stochastic system) causes that projections of anthropogenic climate change have a certain degree of uncertainty (IPCC, 2007). The uncertainties of projections have several sources, some of which were mentioned in the previous section.

Firstly, the specification of future anthropogenic emissions of greenhouse gases and aerosols is uncertain. The anthropogenic emissions depend on the level of population and economic growth and technological development, which in the long term respond to environmental, economic or institutional constraints. Also, the emissions depend on implementation of a range of mitigation policies and actions. Due to their relative unpredictability, in the context of the analyses of climate change these variables are dealt with by emission scenarios – several plausible trajectories of socio-economic and technological development in the future.

Secondly, as mentioned earlier, uncertainty arises within climate models due to the obvious need to simplify the processes in order to implement their mathematical description in the models, and also from the lack of information allowing inclusion of all the processes and factors influencing climate system. This element of projections uncertainty manifests itself though differences between projections from various GCMs.

Lastly, there is a component of uncertainty that results from the inability of GCMs to resolve internal climate variability in sufficient details. This is an important consequence of the stochastic nature of the climate system.

The effects of uncertainty in the knowledge of Earth system processes can be partially quantified by constructing ensembles of models that use different formulation or parameterization of these processes. The multi-model methods are predicated on the fundamental belief that no model is the true model, and there is value in synthesizing projections from an ensemble, even when the individual models seem to disagree with one another.

However, some processes may be missing from the set of available models, and alternative parametrizations of processes may share common systematic biases. Such limitations imply that available model ensembles are not a systematic, exhaustive representation of possible range of distributions of “process parameterization space”, and thus multi-model ensembles are often termed “ensembles of opportunity”. As a consequence, there is an unquantifiable uncertainty even in the envelope of multi-model ensemble results.

The effects of internal variability is normally quantified by running models many times from different initial conditions (the so-called initial condition ensemble), provided that simulated variability is consistent with observations.

In view of the above, it is clear that there is no single, unique answer to the question of climate change signal for a particular location or region. There is a plethora of methods and datasets available, and there seems not to be a scientific consensus as to which are better, more robust and universally applicable. Perhaps the only element of the assessment of climate change signal that gained wide acceptance is the need to work with multiple models and ensemble simulations, which provides a sense of uncertainty involved in determination of future climate. It is also recognized that the GCM simulations alone are not enough to provide plausible, defensible and actionable climate change information. It is more and more common that climate change information is based on the so called "multiple lines of evidence". In this approach, climate change projections are constrained based on ensemble GCMs results, ensemble of downscaled GCM results, analysis of recent historical trends and understanding of physical processes governing local and regional responses.

As the climate change assessment and climate change impact analyses are usually performed in the context of strategic planning, development of adaptation capacity and implementation of climate change adaptation plans, the inherent uncertainty of climate change projections requires management and planning paradigms that can accommodate such uncertainty. Such are unfortunately not common. There are, however, new and developing approaches that are suitable to planning and decision-making under changing and uncertain climate, and these evolve in several directions.

The concepts gaining acceptance are these based on thresholds, tipping-points and consequences. These rely on identification of society's coping ranges and critical thresholds, exceedance of which triggers impacts.

Under "scenario-neutral' and decision-scaling paradigms (Brown et al. 2012; Brown and Wilby, 2012; Prudhomme et al. 2010), sensitivity of a system is explored in response to a wide set of conditions, and system responses are split into classes that have different management/adaptation consequences. Since many possible projection scenarios can fall into a single class, the complexity of multiple scenarios is reduced.

Under "robust-decision making" approaches (Lempert, 2004), instead of seeking decision space for an optimal solution, unlikely to be achieved under combination of competing objectives and significant climatic uncertainties, decisions are preferred which are both robust to uncertainty and accommodating of different environmental, economic and social objectives (Brown, 2011).

Most significantly, the traditional, top-down, data-driven approaches to adaptation are replaced by more appropriate, bottom-up, vulnerability-driven approaches. A traditional top-down approach starts with scenarios of future global change in order to assess the future impact to the organisation or community. This is regarded as sub-optimal because such an approach may miss whom or what is most at risk from climate change and generally provides first order impacts only. A bottom-up approach begins with an assessment of the studied system and the factors that influence its vulnerability to current weather and climate variability (UKCIP, 2009) as well as its vulnerability to other socio-economic factors. In this, the bottom-up approach recognises that climate information is not the only information used in decision-making and planning and is based on a premise that if one is not adapted to the current climate variability and socio-economic environment then it is highly unlikely one will be adapted to a (changed) future climate.

THE OKAVANGO RIVER BASIN

Hydrography, geology and geomorphology

The Okavango system is a part of the endoreic Makgadikgadi basin located in central southern Africa. Based on hydrological differences related to geology, geomorphology and hydrography, the Okavango system can be divided into three parts: the Okavango River catchment, the Okavango Delta and the Boteti sub-basin. The Okavango River catchment can further be divided into four provinces: western headwaters, eastern headwaters, lower basin and the western, inactive drainage system. These basic divisions reflect too, to a certain extent, the major climatic zones of the basin.

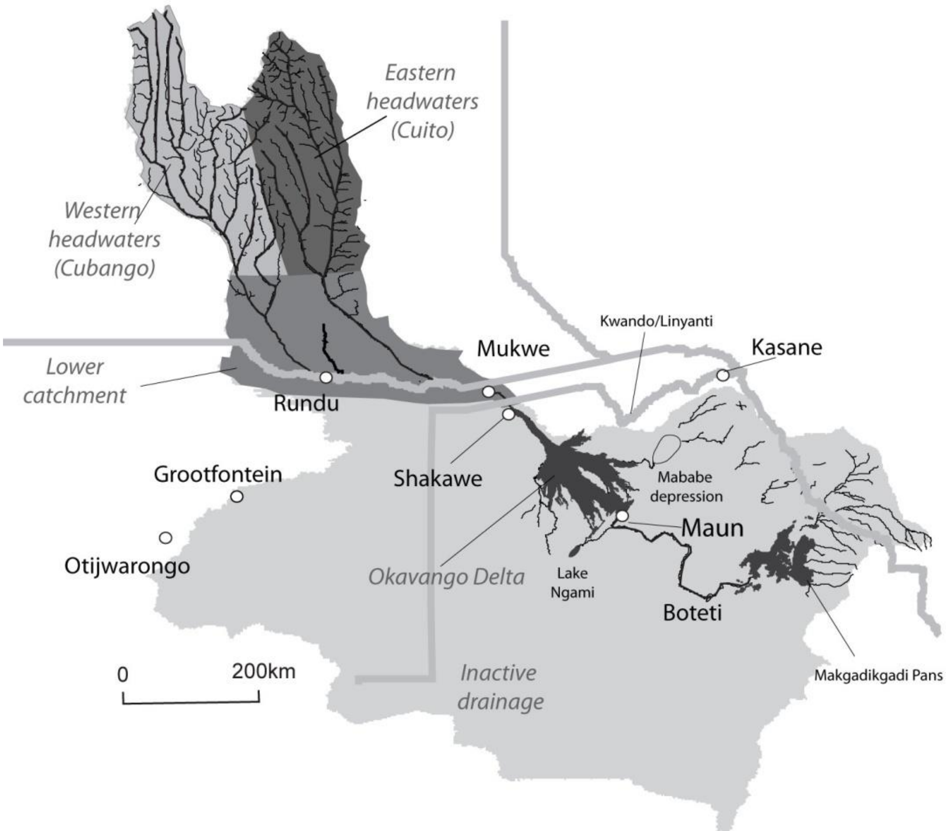


Fig. 1 The Okavango Basin and its principal features

The whole basin, apart from the western headwaters (the Cubango River) where crystalline rocks outcrop, is covered by Kalahari sands. These are highly weathered, well sorted, fine to medium sands, of mixed aeolian-fluvial origin, the nature of which projects strongly on the character of the basin (Thomas and Shaw 1991).

The headwaters of the main tributaries, the Cubango and the Cuito, occupy a topographically higher area (1500–1800 m a.m.s.l.) where mean annual rainfall is over 1200 mm yr^{-1} and the drainage network and topographic relief are well developed. The mid reaches of the Okavango River, the inactive drainage as well as the Delta and Boteti basin, occupy a flat plateau (900–1100 m a.m.s.l) with topographic gradients smaller than 1:3000. This, combined with a very permeable nature of the Kalahari sands, and low rainfall (less than 450 $mmyr^{-1}$), makes the area essentially devoid of structured continuous drainage other than that of the Okavango River. Presence of numerous fossil valleys indicate, however, that in the geological past, rainfall in the region must have been much higher than at present.

The upper part of the Okavango Delta, the Panhandle, is a broad flat-bottomed valley with anastomosing and meandering channels and a system of permanent and seasonal floodplains. The Panhandle broadens into the Okavango Delta proper, which geomorphologically is a large alluvial fan (McCarthy, 1993). The upper part of the fan is occupied by the central swamp; a broad, featureless, permanently inundated area. This separates into four main distributaries, each of which splits into a set of secondary distributaries. There is no consistent channel continuity within the Delta and a large part of the flow takes place in the form of overland flow through a system of interconnected floodplains interspersed with numerous islands, of breadth reaching 20 km. The distributaries terminate at a system of north-east to south-west trending faults, where flows are taken over by rivers collinear with the faults, the Thamalakane and the Kunyere. Two topographic depressions, Mababe depression and Lake Ngami are present at the north-east and south-west extensions of the faults. These at times form lakes, but tend to dry out in drier periods.

The Boteti sub-basin comprises essentially a single river channel of ephemeral character, which terminates in a small alluvial fan in the Makgadikgadi pans. The Boteti River currently receives its water exclusively as a spillover from the Okavango Delta through the Thamalakane River.

During wetter periods, the Okavango Delta connects with the Linyanti and thus Chobe and Zambezi. This linkage is activated when the Makgwekgwana distributary (also known as Selinda spillway) expands and reaches the Linyanti.

Rainfall, runoff and flooding

Rainfall in the basin is highly seasonal, with distinct wet (November–April) and dry (May–October) seasons. There is a clear north-south gradient in annual rainfall amounts, which range from >1200mm yr^{-1} in the Cubango to <400 mm yr^{-1} in the Boteti.

The flow in the Okavango River is perennial, however, with an annual flood event. The runoff from the Okavango River catchment amounts on average to 9306 $Mm^3 year^{-1}$, which is approximately 7% of total average catchment rainfall. Inter-annual variability in rainfall and flows is moderate but there is evidence of dry and wet pluri-annual periods occurring at a number of time scales (see next section).

The flooding in the Delta is predominantly induced by the seasonal flood pulse from the Okavango River. The water flowing in with the Okavango River is supplemented by approximately 4800 Mm^3 $year^{-1}$ falling over the Okavango Delta in the form of local rainfall. This causes the inundation to expand along the Delta, a process that takes about 6 months, with annual minimum inundation occurring in February–March and maximum in August–September (McCarthy et al. 2003). Local rainfall contributes to inter-annual variation in flood extent, but causes expansion of the inundated area only during high rainfall years

(McCarthy et al. 2004). The hydro-period conditions vary throughout the Delta. The central swamp is permanently inundated and is surrounded by a system of seasonally flooded plains, but the frequency of flooding here has large variations from regular annual to once or twice in a 40-year period. These seasonal floodplains are not fixed in space, but migrate, expand and shrink in response to inter-annual and pluri-annual variation in hydrological inputs. Outflow from the Delta through the Thamalakane River averages only 20 Mm^3 $year^{-1}$, which amounts to only approximately 2% of the inputs. With very limited regional groundwater outflows, evaporation in the Delta therefore accounts for 98% of the water. Importantly, however, a significant part of the evapotranspiration takes place through terrestrial vegetation on islands, supplied by floodwater infiltration and lateral groundwater flows of local character (Ramberg et al. 2006). The water balance indicates that this process uses up to 24% of the total inflow (Wolski et al. 2006).

The Boteti flow into Makgadikgadi, and flows into other terminal parts of the Delta, such as Lake Ngami and Mababe depression, as well as flow towards the Linyanti occur only during the wet phases of the multidecadal cycle. Such conditions are present since approximately 2008, and previously occurred in the late 1970s and early 1980s.

Past climate and hydrological variability in the Okavango Basin

Comprehensive determination of past climate and hydrological variability in the Okavango Basin is hampered by the paucity of long-term data. In the recent report assessing status of monitoring networks and trends in water resources in the Okavango Basin (Wolski, 2012), only six long-term rainfall stations (Rundu, Otjiwarongo and Grootfontein in Namibia, and Shakawe, Maun and Kasane in Botswana) and four air temperature stations (Rundu, Shakawe, Maun and Kasane) were identified. No long-term data from Angola were available for the analyses. Because regional climate gradient is relatively simple and smooth, these stations are to a certain extent representative to the overall conditions in the southern part of the Basin. The lack of long-term data from Angola is, however, strongly detrimental to the results and interpretation of analyses of hydro-climatic trends and variability, as it is in Angola where the majority of Basin's water originate. Additionally, the available data do not allow for determination of effects the Okavango Delta (effectively a large oasis) might have on the local climate's response to the global and regional forcings. The shortcomings of the ground observation networks can only to a certain extent be overcome by the use of alternative data products such as CRU, UDEL, GPCP or WATCH, as these introduce additional uncertainties related to data sets included in their preparation and processing procedures – to the extent that there are differences, sometimes significant, between them.

Hydrometric network suffers from similar deficiencies as the climate and weather monitoring, i.e. the lack of long-term data from the Angolan part of the catchment. The lack of measurements of the discharges of the Cuito River is particularly problematic, as that river seems to be a key to understanding of the role of multidecadal variability in the system.

Rainfall

Station data indicate an overall negative long-term trend in total annual precipitation, although this trend is not statistically significant (Table 1).

There is a strong, statistically significant evidence of presence of extended wetter and drier periods in rainfall time series (all stations but Grootfontein and Otijwarongo). In particular, the period of 1979-2009 is significantly drier than the preceding 30 years. Similar effect is seen in rainfall reconstructions for the headwaters of the Okavango River (Fig. 3).

Piece-wise trends (assessed only for Botswana stations) are somewhat consistent with trends in river discharges (decrease in 1979-1989, but only weak increase in 1990-2009), and are not statistically significant (Table 1).

In terms of seasonality, there seems to be a long-term shift in seasonal distribution of rainfall, with an increase in January rainfall, and decrease in February and December (results not explicitly presented here). The shift is not statistically significant. Additionally, there is an indication of an increase in rainfall variability, but no statistical significance can be attached to this result. Other indices of rainfall – such as frequency of rain days, duration of dry and wet spells, daily rainfall percentiles also do not display significant long-term trends.

Table 1 Summary of variability in rainfall measured at long-term stations (after Wolski, 2012)

	Rundu	**Grootfontein**	**Otjiwarongo**	**Maun**	**Shakawe**	**Kasane**
Time period	1944-2010	1917-2009	1913-1997	1922-2009	1922-2009	1933-2009
Long-term trend, total annual rainfall	Negative $p>0.1$*	None	none	Negative $p=0.82$	Negative $p=0.42$	Negative $p=0.21$
Dry-wet phases	**1978-2005 drier than earlier and later, $p<0.01$****	Not significant	Not significant	**1979-2009 drier than preceding 30 years $p=0.01$****	**1979-2009 drier than preceding 30 years $p=0.03$****	**1979-2009 drier than preceding 30 years $p=0.04$****
Trend in maximum daily precipitation	Negative, not significant (no p value given)	Not assessed	Not assessed	Not assessed	Not assessed	Not assessed
Monthly trends	Increase in January, $p\sim0.1$* Decrease in February, $p\sim0.1$* and other seasons	Increase in January, no p value given	Increase in January, no p value given	Increase in Jan, decrease in Dec & Mar, $p>0.05$*	Increase in Jan, decrease in Dec and Feb, $p>0.05$*	Decrease in Dec, Jan and March, p>.0.05*
Piecewise trends 1970-1989	Not assessed	Not assessed	Not assessed	Negative $p=0.31$*	Negative $p=0.77$*	Negative $p=0.65$*
1990-2009				Positive $p=0.99$*	Positive $p=0.99$*	negative $p=0.88$*

*Mann-Kendall test, ** Mann-Whitney test, ***runs test, ****trend in CV

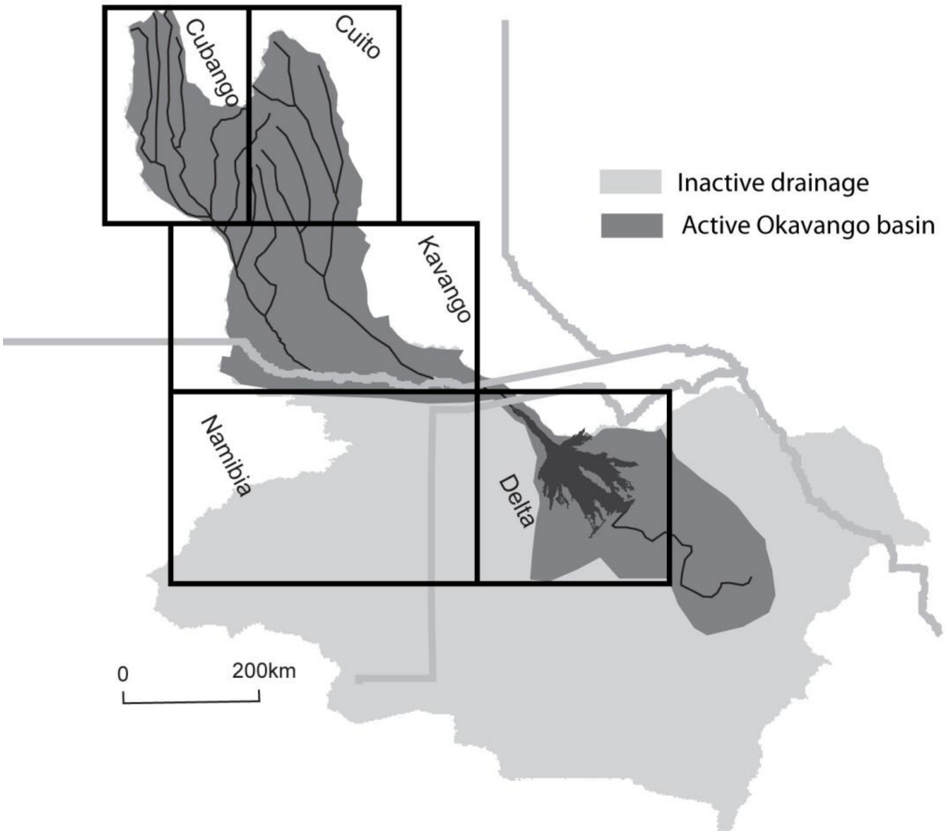


Fig. 2 Zones used for analysis of gridded rainfall and temperature products

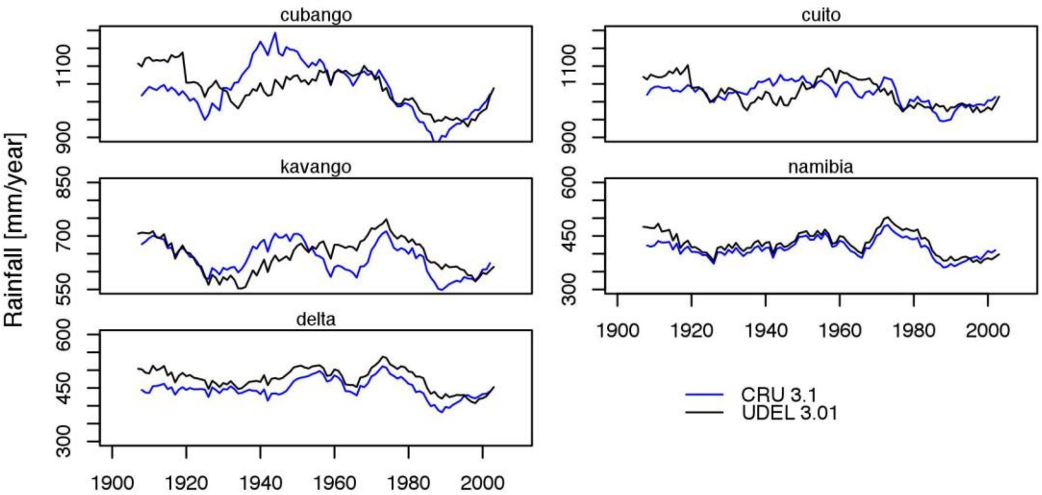


Fig. 3 15-year running averages of rainfall in the Okavango basin. Zones as in Fig. 2.

Air temperature

Results of analyses of trends and variability of air temperature for the key stations in the southern part of the Basin, as well as air temperature reconstructions are summarized in Table 2 and Fig. 4.

Table 2 Summary of trends in temperature at long-term stations (after Wolski, 2012)

Location	Rundu	Maun	Shakawe	Kasane
period	1985-2010	1965-2009	1961-2009	1985-2009
Mean minimum temperature		**Positive, p<0.001**	Negative, p=0.34	**Negative, p<0.001)**
Mean maximum temperature	Positive, p>0.1	**Positive, p=0.001**	**Positive, p=0.001**	**Negative, p=0.02**
Seasonal effects, minimum temperature		**Increase in all seasons**	No significant trends	**Decrease, strong in winter**
Seasonal effects, maximum temperature		**Increase in March-September**	**Increase in March-September**	No seasonally-coherent signal

Results significant at 0.05 level in bold, tests based on linear regression

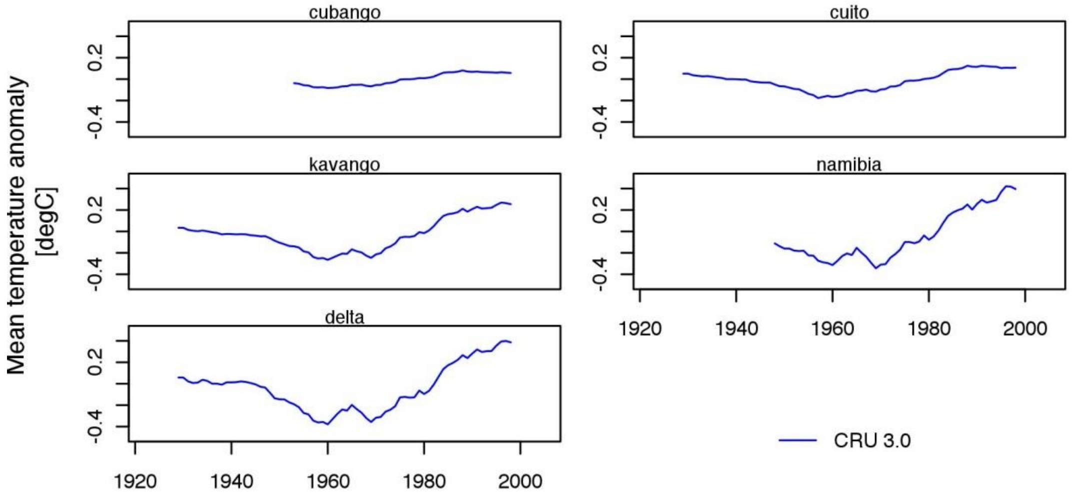


Fig. 4 15-year running average of mean annual temperature in the Okavango basin. Zones as in Fig. 2.

There is relatively little coherency between stations in terms of longer-term trends for annual mean temperatures (Table 2). A positive, although statistically not significant trend is present in the Rundu mean maximum temperature. Similar, but significant trend is present in Maun and Shakawe mean maximum temperatures, but a negative trend is present in Kasane. For annual mean minimum temperatures, a significant positive trend is observed in Maun, a non-significant negative trend is present in Shakawe and a significant negative trend in Kasane.

Seasonal trends are also not consistent between stations. Minimum temperatures show increases in all seasons at Maun, but no significant trends are present in Shakawe, while significant decreases are observed in winter months in Kasane. Maximum temperatures show increases in March-September at Maun and Shakawe, but no seasonally coherent signal at Kasane.

Overall, these results are to be treated with care, as these were obtained using data provided by countries' meteorological services as is, without quality control. In particular, Kasane data seem suspect, and it is possible that they contain non-homogeneity (moving of the station or similar), but no information could be obtained to confirm/deny this.

Gridded dataset, CRU3.1, shows a strong statistically significant increase in mean maximum temperatures and mean minimum temperatures in the period between mid-1940s till 2009 (in all zones), with $p < 0.001$. There is a decrease in temperatures observed in the preceding period (Fig. 4).

River discharges

There is a weak negative trend in Okavango River discharges downstream of Cuito confluence (in Cuito, Mukwe and Mohembo) in the period of record (1940s-present). Trend in the Cubango (at Rundu) appears to be weakly positive (Table 3).

The nature of interannual variability in the Okavango (illustrated in Fig. 5) causes that the significance of long-term trends depends on the length of the analysed time series. This is clearly illustrated by the example of Mukwe record where the inclusion of just 3 years at the end to the time series has changed the trend from statistically significant to not significant. Also, the strongly negative trends observed in Thamalakane and Kunyere discharges during the period of record seem to be artefacts of the relatively short time series, with the high phase of 2000s too short to compensate for the earlier pattern of high (1960-1970s)-low (1980-1990s) phases. Thus, the long-term trends presented above have to be treated with caution, as their significance may change within the next years.

Multi-year periods could be identified which significantly differ in mean discharges. In general, the period around 1980-1990 appears to be drier than the preceding and following years. Longer-term data from Mohembo (Fig. 5) as well as the gridded rainfall data (Fig. 3) indicate that another dry period occurred in 1920-1930s.

Piecewise trend analysis indicates a strong and significant decadal-scale negative trend in the Okavango river discharges at Mohembo in the period of 1976-1996, and a significant positive trend since 1997. Although not explicitly analysed, similar patterns are present in Mukwe and Rundu records.

There is an indication that interannual variability of river discharges has reduced throughout time, but the method used in the analysis (trend on highly autocorrelated time series of moving-window's coefficient of variation, CV) does not allow for determination of statistical significance of this finding.

Discharges in the rivers downstream of the Okavango Delta (terminal rivers) replicate the main features of the inflows registered at Mohembo: trends observed in the recent years, relatively high level of interannual persistence, and presence of multi-year periods of above average or below average discharges (Table 4). Seasonal dynamics differ between the terminal rivers, depending on the character of the system of floodplains and hydrological connectivity within the distributaries they drain. Additionally, discharges of the terminal rivers are affected by changes in distribution of water between the distributaries within the Okavango Delta, with the Kunyere system receiving a larger proportion of Okavango Delta inflow since 1997 than it used to before that date (Wolski & Murray-Hudson, 2008).

Discharges of the ephemeral/seasonal Omatako River located within the Namibian part of the Basin, are characterized by overall positive trend during the 1961-2000 period, although this trend is not statistically significant (Table 4).

Table 3 Summary of results of the analyses of trends in Okavango river discharges (total annual flows) upstream from the Okavango Delta (after Wolski, 2012)

	Cubango @ Rundu	**Cuito (obtained as a difference between Mukwe and Rundu discharges)**	**Okavango@ Mukwe**	**Okavango@ Mohembo**
Time period	1946-2010	1949-2007 (2010)	1949-2007 (2010)	1934-2010
Long-term trend Total annual discharge	Positive p>0.1***	**1949-2007 and 1949-2010 Negative p<0.01***	**Negative 1949-2007 p<0.01*** 1949-2010 p>0.1*	Negative p=0.39*** (p=0.039)****
Long term trend Maximum monthly discharge	Not assessed	Not assessed	Negative, p not given	Negative p=0.84*** (p=0.84)
Long term trend Minimum monthly discharge	Not assessed	Not assessed	Not assessed	**Negative p<0.001***** **(p<0.001)******
Dry-wet phases	**1970-1997 drier than 1949-1969 p<0.05****	Not assessed	**1984-2002 drier than 1949-1983 p not given**	**1980-2010 drier than 1950-1979 p=0.01** (p=0.0001)******
Piece-wise trends	**1976-1995 Negative p=0.01***** **(p=0. 01)** **** **1995-2010 Positive p=0.001** *** **(p<0.001)** ****	Not assessed	Not assessed	**1976-1995 Negative p<0.001***** **(p<0.001)** **** **1995-2010 Positive p<0.001** *** **(p<0.001)** ****
Trend in CV	Negative	Not assessed	Negative	Not assessed
Autocorrelati on	Low (r~0.13 within 3 years)	Strong r=0.45-0.1 within 15 years	Moderate r=0.35-0.2 within 3 years	Strong: r=0.44-0.27 in within 3 years

* linear regression **Mann-Whitney rank test *** Mann-Kendal test **** Mann-Kendal test with bootstrap significance level
Effects significant at 0.05 confidence level in bold

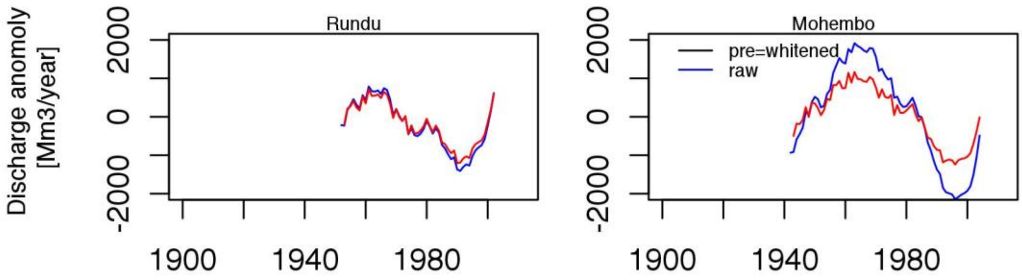


Fig. 5 15-year running averages of discharges of the Okavango River at Rundu and Mohembo. Pre-whitened series illustrates residual long-term pattern remaining after removing significant auto-correlation from the original time series (after Wolski, 2012)

Table 4 Summary of results of the analyses of trends in Omatako, Thamalakane and Kunyere river discharges (after Wolski, 2012)

	Omatako	**Thamalakane**	**Kunyere**
Time period	1946-2010	1968-2010	1974-2010
Long-term trend, total annual flows	Positive p>0.1*	**Negative p<0.001* (p<0.001)****	Positive p>0.92* (p=0.91)**
Long-term trend Maximum monthly discharge	Not assessed	**Negative p=<0.001* (p<0.001)****	Positive p=0.73* (p=0.72)**
Long-term trend Minimum monthly discharge	Not assessed	Negative p=0.26* (p=0.26)	Not assessed
Piece-wise trends	Not assessed	**1976-1995 Negative p<0.001* (p<0.001)** 1996-2010 Positive p=0.002* (p=0.001)****	**1976-1995 Negative p=0.015* (p=0.015)** 1996-2010 Positive p<0.001* (p<0.001)****

*Mann-Kendal test **Mann-Kendal test with bootstrap significance level
Effects significant at 0.05 level in bold

Summary: Is there anthropogenic climate change signal in Okavango Basin's climate and hydrological responses?

Considering the nature of the anthropogenic climate change set against the background of natural climate variability, as described in section 1, it is usually considered that only trends in climatic variables persisting at time-scales longer than 30-50 years are indicative of possible anthropogenic influence.

There is little evidence for overall long-term (since the beginning of the 20th century) trend in climate and river flows in the Okavango basin. There is, however, a relatively strong evidence of multidecadal scale variability present in rainfall, air temperatures and river discharges. This variability is manifested by differences between means of 30-year non-overlapping periods, which are statistically significant in station rainfall, gridded rainfall and in river discharges. The effect is generally stronger in the downstream locations, particularly downstream of the Okavango Delta, but is not evident in the ephemeral part of the basin in

Namibia. For rainfall and river discharges, the presence of high and low (or wet and dry) phases in the long-term takes the form of oscillatory-like pattern, with a low phase in 1920-1930s, a high in 1950-1970, a low in 1980-1990s, and an onset of high phase in the 2000s. There is some similarity between rainfall and river discharge patterns. Significantly, recent gridded rainfall data reveal increased rainfall after the mid 1990s, an effect not visible in the earlier studies.

The current interpretation of this multidecadal pattern is that it is caused by natural variability in the climate system, possibly related to the global modes of variability such as Pacific Decadal Oscillation (PDO), or North Atlantic Oscillation (NAO) (Wolski, 2012; Jury, 2010; Jury, 2012). It is widely recognized that these modes are naturally occurring, and are only modified by the anthropogenic climate change, and not caused by it. With this understanding it is impossible to unconditionally extrapolate the post-1996 trend in rainfall and river discharges into the future. Between 2000 and 2009 the system has entered a wet phase, and it is likely, but not certain, that it will remain there in the next decades.

Importantly, as the example of the discharges at Mukwe indicates (Table 3), where the inclusion of just 3 wetter years at the end of the record changes the significance of the long-term trend, long-term trends described here have to be looked at and assessed in the context of the multidecadal variability.

Although there seems to be a negative trend in rainfall in the Okavango headwaters and in the Delta, these are not statistically significant and are potentially affected/caused by the multi-decadal variability, with the recent wetter period captured for too short a period to compensate for effects of rainfall decline observed in the 1980s and 1990s.

The only statistically significant long-term trends are the negative trends in total annual discharges of the Cuito and in the minimum monthly discharges of the Okavango at Mohembo. These might potentially be caused by the influence of the increasing temperatures on evaporation in the catchment. Baseflow (reflected in minimum monthly discharges) is determined by groundwater storage in a catchment, which is normally affected by transpiration and thus increasing temperatures. Since runoff from the Cuito catchment is dominated by groundwater response, it is possible that such a mechanism is in play there. This theory is, however, tentative, and demands elaboration, which is beyond the scope of this study.

Trends in air temperature are difficult to generalize, particularly because the available data series are relatively short (at best, station data analysed here cover the period after 1961). At Maun, there is a clear trend towards higher values in minimum monthly temperature, for each month. There seems not to be any clear trends in Shakawe and Rundu, and actually reduction in wintertime temperatures in Kasane. The trends are statistically significant only in the long-term (>50 years), while no statistical significance is attained by the recent 30-year trends. For Maun and Shakawe, the long-term temperature patterns are consistent with the increase in temperatures expected from anthropogenic climate change. The pattern of reduction of temperatures in Kasane should be studied more extensively to reveal its causal factors.

CLIMATE CHANGE PROJECTIONS FOR THE OKAVANGO BASIN

Approaches, models and datasets

There are a number of studies available in published scientific literature and as technical consultancy reports, assessing impacts of climate change on the hydrology of the Okavango basin and the Okavango Delta (Wolski, 2002; Bauer, 2004; Scanagri, 2005; Andersson et al. 2006; Murray-Hudson et al. 2006; Wolski & Murray-Hudson, 2008; Milzow et al., 2010; Wolski, 2009; Hughes et al. 2011; Wolski et al. 2012, Wolski et al. submitted). The studies differ in climate projection datasets, data processing methods, hydrological models, and definition of impacts. They also differ in geographical scope: some address the Okavango catchment (upstream from Mohembo), some deal with the Okavango Delta only, although, obviously the assessment of impact on the Delta accounts for transformation of hydrological fluxes in the catchment.

Geographical scope of earlier studies

Only four studies deal with determination of climate signal and simulations of the Okavango River responses to changing climate upstream of the Okavango Delta (Table 5): Andersson et al. (2006) in the framework of Water and Environmental Resources for Regional Development Project (WERRD), Wolski (2009) in the framework of Environmental Flows Assessment and Transboundary Diagnostic Analyses (EFA/TDA) project, Hughes et al. (2011) in the framework of Quantifying and Understanding the Earth System (QUEST) programme, and finally, Wolski et al. 2012. Currently, work on the climate change influence on the Okavango basin is carried out in the framework of The Future Okavango project (TFO), and first results are already available (Weber et al. 2013), although at this stage are restricted to climate variables only.

Table 5 Studies of climate change impact on the Okavango River discharges (upstream from Mohembo)

Study	Hydrological model	GC models	Future periods	GHG scenario	Method
Andersson et al.2006 (WERRD)	Pitman (semi-distributed, semi-conceptual)	5 (CCC, GFDL, CSIRO, HadCM3, NIES99)	2020-2050 2050-2080 2070-2099	SRES A2 SRES B2	Change factor, GCM data
Wolski, 2009 (EFA/TDA)	Pitman (semi-distributed, semi-conceptual)	9 (CMIP3)	2046-2065	SRES A2	Change factor, downscaled data (SOM-D)
Hughes et al. (2011) (QUEST)	Pitman (semi-distributed, semi-conceptual)	7 (CMIP3)	Not applicable	Not applicable	Change factor, pattern scaling of GCM data
Wolski et al. 2012	Pitman (semi-distributed,	18 (CMIP3)	2000-2100	SRES A2	Direct simulation, Bias corrected

Wolski et al. submitted	semi-conceptual) Pitman (semi-distributed, semi-conceptual)	2 (HadAM3P and CAM5.1)	2009-2012 as compared to pre 1860	Not applicable	GCM data Direct simulations, bias-corrected and statistically dowscaled GCM data

Most of the studies dealing with determination of climate change impacts on the Okavango Delta (Table 6) utilize results of simulations of the Okavango River flows under projected climates obtained within the WERRD project (Andersson et al. 2006), and only the ones by Wolski (2009) and Wolski et al. (2012) use dedicated simulations of Okavango River flows.

Table 6 Studies of climate change impact on the hydrology and hydro-ecology of the Okavango Delta

Study	Source of catchment flows	Hydrological model	GC models	Future period	GHG scenarios	Method
Wolski, 2002	none	statistical	hypothetical	n.a.	n.a.	n.a.
Bauer, 2004	none	Bauer, 2004; also Bauer et al. 2006, based on MODFLOW (fully distributed)	hypothetical	n.a.	n.a.	n.a.
Scanagri, 2005 (ODMP)	WERRD	MIKE SHE (fully distributed)	HadCM3	Not specified	Not specified	Change factor, GCM data
Murray-Hudson et al. 2006	WERRD	Wolski et al. 2006 (semi-lumped)	3 (CCC, GFDL, HadCM3)	2020-2050 2050-2080	SRES A2 SRES B2	Change factor, GCM data
Wolski and Murray-Hudson, 2008	WERRD	Wolski et al. 2006 (semi-conceptual)	3 (CCC, GFDL, HadCM3)	2046-2065	SRES B2	Change factor, GCM data
Alemaw, 2009	none	Alemaw, 2009	HadCM2 and UKTR	2050	Not specified	Change factor, GCM data
Milzow et al. 2010	WERRD	Enhanced version of Bauer, 2006 (fully-distributed)	5 (CCC, GFDL, CSIRO, HadCM3, NIES99)	2040–2069 2070–2099	SRES A2	Change factor, GCM data
Wolski, 2009	Dedicated simulations	Wolski et al. 2006 (semi-lumped)	9 (CMIP3)	2046-2065	SRES A2	Change factor, downscaled data
Wolski et al. 2012	Dedicated simulations	Wolski et al. 2006 (semi-lumped)	18 (CMIP3)	2000-2100	SRES A2	Direct simulation, bias corrected GCM data

Uncertainty of projections

The studies differ in how the uncertainty of climate signal, particularly the model uncertainty (see the Introduction section) is treated and expressed. This partly results from the timing of studies set against availability of data and evolution of the understanding of need for ensemble simulations. While the early studies used data from 3-5 GCMs, recent studies utilize 40 runs of 18 different GCMs, thus having a better chance of properly spanning the range of uncertainty. Surprisingly, study by Scanagri (2005), which was the basis for development of the Okavango Delta Management Plan, has used only one GCM – HadCM3, which was arguably frequently used in the past, and which happen to be one of the "drier" models – thus potentially misinforming the process of formulation of ODMP by not expressing the whole range (or at least a large proportion) of uncertainty associated with climate change projections.

Wolski et al. (2009) in a study that utilized downscaled data provided three scenarios – "dry", "moderate" and "wet", which corresponded to 25, 50 and 75th percentiles of inter-model spread. In the ensemble of 9, the marginal percentiles effectively screened off the extreme dry and extreme wet models. In this way, both spread and consistency of projections from various models were taken into account, but the final results were not affected by extreme projections from a single model.

Hughes et al. (2011), apart from capturing GCM uncertainty by using 7 different GCMs, explicitly addressed the uncertainty resulting from the hydrological model. To achieve the latter, parameters of the hydrological model were randomly varied and hydrological model was run driven by GCM data in a 1000-sample Monte-Carlo setting.

Linking climate data to hydrological models

Majority of studies used the change factor, or perturbation approach. In this approach, differences between future and past rainfall and air temperature determined from a GCM on a monthly basis were used to modify observed time series of hydrological model inputs. The advantage of the method is its simplicity, and in fact, this method is sometimes considered to be a simple downscaling approach.

The important limitation of the change factor method is that it accounts only for mean change in rainfall or temperature and it does not account for possible change in variability and persistence, particularly at time scales longer than a year. As a consequence, when applied in the Okavango system, the change factor procedure faces an important conceptual problem. The Okavango system is characterized by multidecadal variability taking the form of 20-30 year periods when rainfall systematically deviates from long-term mean. Mean climate change signal derived as a bulk change factor does not inform about possible differences in climate change influence on low and high phases of that variability. Also, additional uncertainty arises that is related to the fact that if similar multidecadal oscillations do actually occur in the GCM climate, by virtue of GCMs treatment of natural variability it is not necessary that these are time-consistent with observations. Thus change factor, which is calculated on the basis of 20-30 year periods, may be inflated, or reduced by the multidecadal oscillations. The study by Wolski et al. (2012), had overcome this problem by explicitly using GCM output to drive hydrological models. The drawback of this "direct" approach was that GCM variables had to be bias corrected to fall within a feasible range, so as they could be applied to hydrological models without forcing unrealistic regimes.

Downscaling

Majority of the studies used GCM data though change factor approach. Only Wolski (2009) performed proper downscaling using SOM-based statistical downscaling procedure

(Hewitson and Crane, 2006). This procedure uses observed rainfall and reanalysis data (model and observations-derived variables describing state of the atmosphere) to define a stochastic function between local rainfall and pattern of synoptic conditions in the region. This function is later applied to synoptic fields generated by a GCM in order to derive rainfall time series at a location of a given station. This method does not utilize rainfall figures produced by a GCM, which is a notoriously uncertain variable. Instead, it uses a set of variables that describe state of the atmosphere in the broad vicinity of the gauge site, which are arguably more robust output of GCMs. Overall, it has been shown that this method reduces inter-GCM spread (Hewitson and Crane, 2006).

Hughes et al. (2011) use climate fields generated by ClimGen “pattern scaling” technique described in detail in Todd et al. (2011). The fundamental assumption of ClimGen is that the spatial and temporal pattern of change in climate as simulated by a GCM with a given change in global average temperature can be linearly rescaled to represent the pattern of change in climate associated with a different global temperature change. Although ClimGen provides scenarios down to a spatial resolution of 0.5×0.5 deg, this is achieved by interpolation rather than a proper downscaling. The characteristic of ClimGen scenarios is that these are expressed in terms of conditions for a particular change in global mean temperature rather than in terms of future time slice.

Recent study carried out within the TFO project is using dynamical downscaling (Weber et al. 2013). In the TFO approach, the downscaling is realized with a double-nested system of GCM-RCM-RCM models, with the resolution of output of 0.22×0.22 deg. Eight simulations are planned, being a combination of two forcing GCMs, two RCMs (REMO and WRF) and two future concentration pathways (RCP4.5 and RCP8.5), four of which were reported upon at the time of preparation of this report.

Impact indices

Climate change impacts on hydrological conditions in the Okavango system were assessed in the earlier studies using a number of indices.

For the Okavango River, these indices were mean monthly discharges, as well as multi-year flow duration curves. Hughes et al. (2011) also presents assessment of timing of flood peak.

For the Okavango Delta, by the virtue of the dynamic nature of this wetland system, simple hydrological indices (mean monthly discharge and flow duration and inundated area) do not appropriately reflect hydrological and hydro-ecological conditions and their change. In the Okavango Delta it is the total area and position of functional hydro-ecological units such as permanent swamp, seasonal floodplains, occasionally inundated floodplains and dryland that underlies ecological functioning of the wetland. These units are dynamic, but have a certain “inertia”, i.e. transform from and to one another, but only under persistent change in flooding conditions. Recognizing this dynamics, Murray-Hudson et al. (2006) and Wolski & Murray-Hudson (2008) developed a relationship linking occurrence of these units to history of inundation (duration and intermittency in 5-year prior). In this way, ecological status of the system could be ascertained at any moment rather than during an arbitrary period of time.

The need to use vegetation rather than hydrological variables as a basis for an impact index has also been recognized by Milzow et al. (2010). They considered that occurrence of vegetation classes in the Delta can be functionally related to prevalent groundwater depth, and developed a probabilistic function describing that relationship for each vegetation type. This allowed representation of climate change impacts though change in probabilities of occurrence of various vegetation classes at a particular location.

Another important aspect related to the impacts on the Okavango Delta is that of multidecadal variability. As a result of the natural 20-30 year and longer "dry" (below average) or "wet" (above average) sequences, hydro-ecological units change – move, expand or shrink. These natural changes, and of course also changes in the simple hydrological indices, are comparable in magnitude to the changes induced by anthropogenic climate change. In such a situation, using mean change is essentially meaningless, as similar effects occur naturally. Murray-Hudson et al. (2006) solved that problem by determining impacts separately for "wet" and "dry" multidecadal regimes. The implicit assumption behind such an approach was that the "wet" and "dry" sequences observed in the past will also occur in the future, although the mean conditions during each of them will be modified by the effects of climate change.

Wolski et al. (2012), focusing on multidecadal variability, used discharge of the terminal Boro river as an expression of conditions in the Okavango Delta.

Very little attention has been put on an explicit assessment of extreme events in the system, as majority of the studies have been concerned with mean conditions as exemplified by the mean annual hydrograph. This is partly due to methodological limitations – the frequently used change factor method used with 20-30 year time windows does not allow for conceptually sound, explicit assessment of change in the distribution of extreme flows. Nonetheless, Wolski (2009) have presented a set of flow duration curves under past and projected climates, which can be interpreted in terms of change in frequency of occurrence of high (although perhaps not extreme) flows and duration of no-flow (hydrological drought) conditions. Importantly, due to the modelling framework utilizing a monthly model, these "extremes" changes are reflections of changes in mean rainfall and temperature, and are not per-se related to extreme meteorological events.

In a recent study, Wolski et al. (submitted) explicitly addresses the influence of anthropogenic climate change on the probability of occurrence of the high floods of 2009-2011 period. That study is not a classical climate-change projection one. Rather, it is a climate change attribution study where it is assessed how the current climate change have influenced the probability of (or risks of) events with magnitude of the actual, observed events. The study uses the monthly model, but it explicitly looks at change in probability distribution function of mean annual and maximum annual discharges of the Okavango River between the pre-industrial and current climates simulated with two GCMs.

The forthcoming results by TFO project (e.g. Weber et al. 2013) create a promise of a sound assessment of future extremes, as they will be based on a daily dynamically downscaled climate and a daily hydrological model. At the time of writing this report, only some climate simulations were completed, and these have not yet been linked to the hydrological model.

Results

Climate change signal in climate variables

Majority of the studies presented here used GCM data included in the PCMDI CMIP3 archive (www-pcmdi.llnl.gov) that was the basis for IPCC 2007 Fourth Assessment Report.

While the studies were concerned with hydrological impacts, it is interesting to present projected change in climate itself, as this information is relatively straightforward and independent on the choice of impact model/relationship. Climate change signal for 18 GCMs, and 9 downscaled GCMs, based on Wolski (2009) is summarized in Fig. 6, Fig. 7 and Fig. 8. For 2046-2065, under SRES A2 scenario, CMIP3 GCMs project an overall increase in mean air temperature in the order of 1.5-3 deg C. That increase in similar during each season, and appears to be somewhat stronger in the southern part of the Basin, i.e. in the Delta region. As for rainfall – there is a strong divergence between GCMs. Overall change on annual basis falls within -35% to +15% depending on the GCM, with stronger reduction in austral winter (June-July-August – JJA in Fig. 6) and in the beginning of rainy season (September-October-November – SON in Fig. 6).

The statistically downscaled data indicate a narrower range in temperature projections than these obtained from raw GCMs – falling within 2-3,5 deg C, although this narrower range may be caused by the fact that fewer GCMs are used in downscaling. In terms of rainfall – majority of downscaled GCMs project increase in annual rainfall. Also, majority of GCMs project increases in late rainy season and winter rainfall (March-April-May – MAM and JJA in Fig. 7), while there is an approximately equal split between GCMs projecting increases and decreases in rainfall in the remaining seasons.

Downscaled data allow for assessment of changes in rainfall and temperature indices that are derived from daily data (GCM data, although available as daily, are typically used only at monthly time scales). Fig. 8 indicates that for Maun, minimum daily temperature is projected to increase by 2.2-3.4 deg C, while maximum daily temperature may increase within a narrower range: 2.4-3.0 deg C. There is no consistent signal in terms of number of hot days. In terms of rainfall – daily downscaled data indicate that the overall increase in rainfall results from the increase in number of rain days rather than change in intensity, with an associated decrease in dry spell duration. Importantly, out of the changes in daily temperatures and rainfall indices – only changes in minimum and maximum temperatures are statistically significant. Other changes fall within ranges expected by the virtue of observed variability.

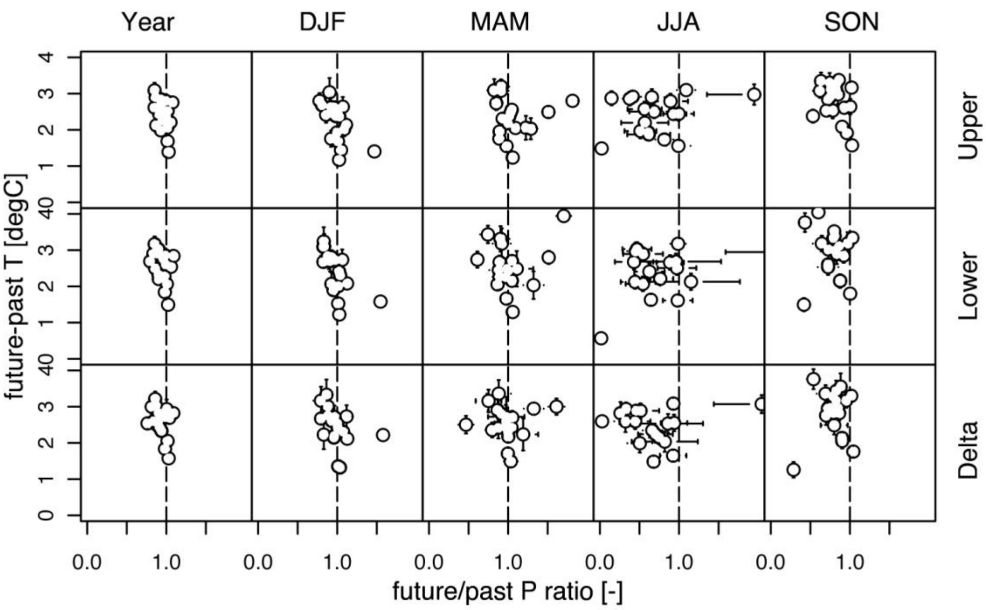


Fig. 6 Climate change signal in the Okavango Basin, based on 18 CMIP3 GCMs, SRES A2 emission scenario, 2046-2065 period, compared to 1960-1990 (after Wolski, 2009). Delta – Okavango Delta, Lower – Okavango catchment between 15 and 18 deg S, Upper – Okavango catchment north of 15 deg S.

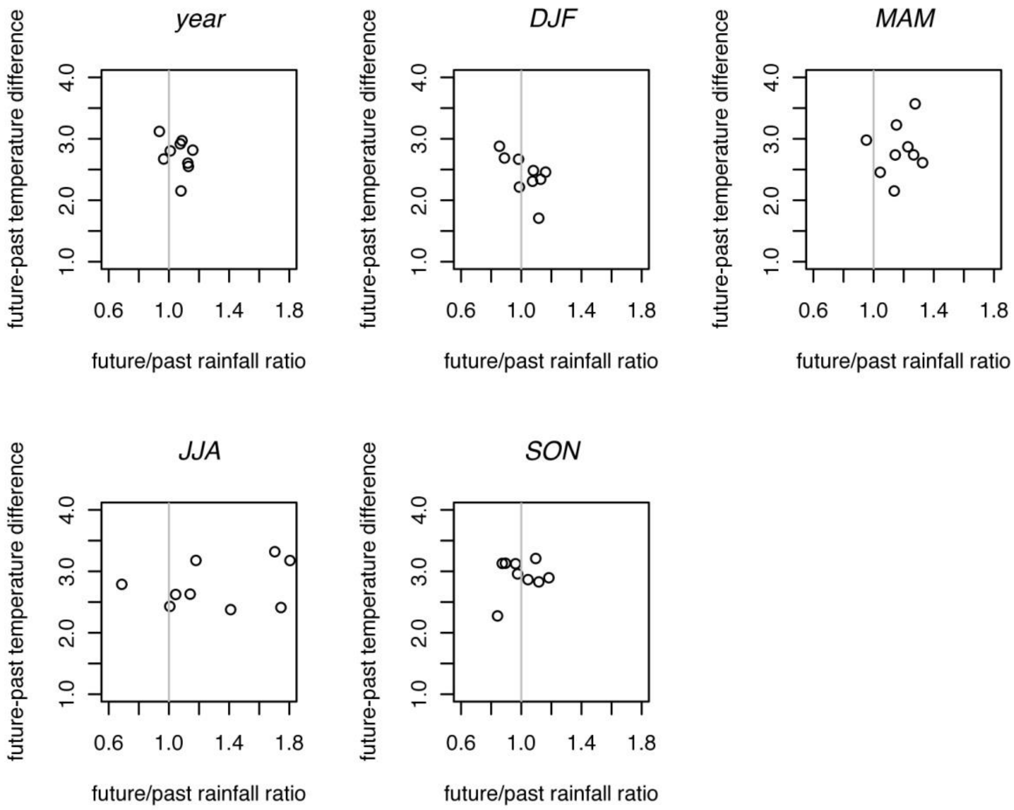
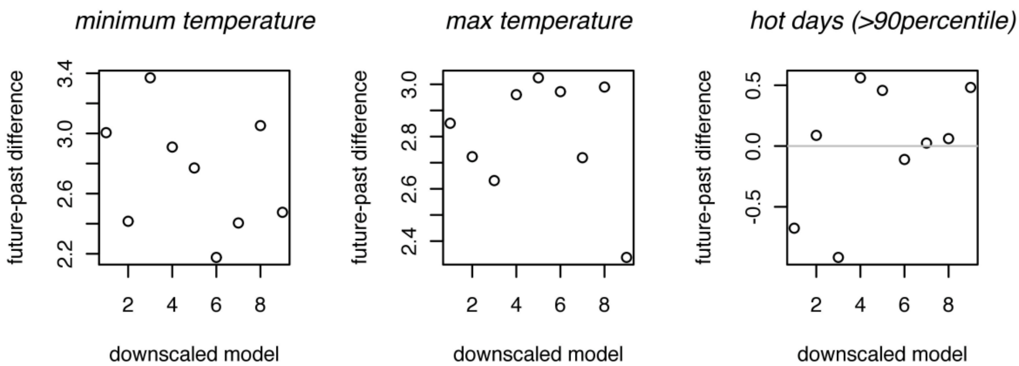


Fig. 7 Climate change signal for the Okavango Delta, based on 9 downscaled CMIP3 GCMs, SRES A2 emission scenario, 2046-2065 period, compared to 1960-1990 (after Wolski, 2009)



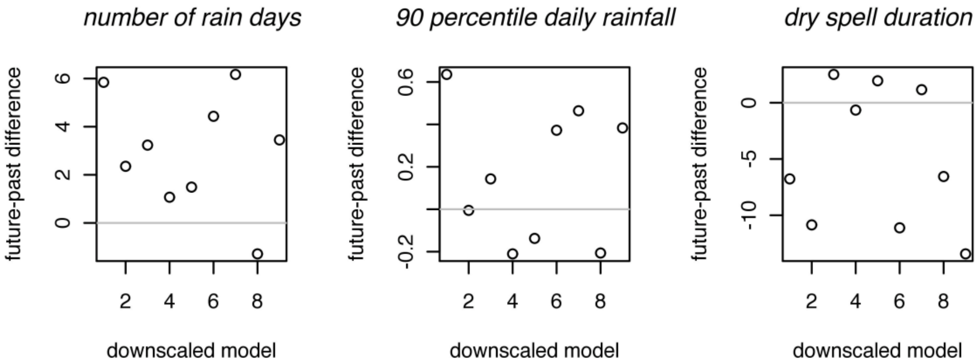


Fig. 8 Climate change signal at Maun for indices derived from daily data, based on 9 dowscaled CMP3 GCMs, SRES A2 emission scenario, 2046-2065 period compared to 1960-1990 (after Wolski, 2009)

The TFO project results (Weber at al. 2013), which are based on simulations with a high-resolution RCM, indicate, similarly to the earlier GCM-based work, a degree of divergence between models and GHG concentration pathways, and additionally, a high degree of spatial heterogeneity of responses. The change in temperature is unequivocal, although differs strongly (approx 2 deg C and approx. 5 degC) between the two GHG concentration pathways considered (left-hand side panel in Fig. 9). There is a difference in direction of change in rainfall between the northern and southern part of the catchment, with the former projected to increase or change little in all simulations (Fig. 10), which is also accompanied by increase in rainfall intensity and shortening of rainy season. Basin-average rainfall is projected to decrease throughout the 21st century, although one of the 4 combinations of GCM/RCM/RCP indicates a lack of change in that factor (right-hand side panel in Fig. 9).

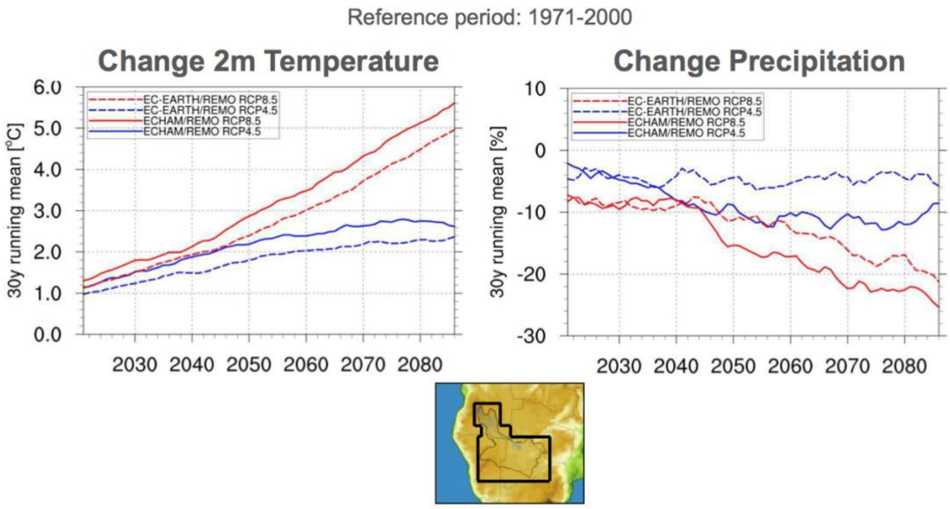


Fig. 9 Trajectories of 30-year running averages of air temperature and precipitation through 21st century, simulated by 4 combinations of GCM-RCM-GHG concentration pathways. From Weber et al. 2013.

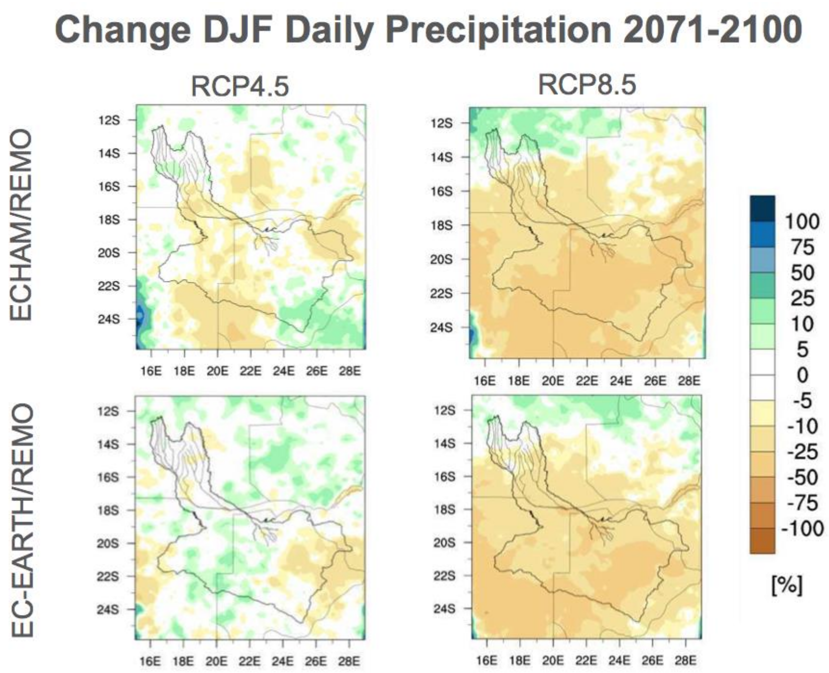


Fig. 10 Change in daily precipitation in DJF in 2071-2011 as compared to 1971-2000, simulated by 4 combinations of GCM-RCM-GHG concentration pathways. From Weber et al. 2013.

Impacts on the Okavango River

The analyses performed in the WERRD project revealed an important fact. Namely, there were major differences between various GCMs in terms of projected change river discharges, to the extent that some GCMs were projecting increase, while others were projecting decrease in rainfall (Fig. 11). The magnitude of changes varies relatively strongly between GCMs, emission scenarios and future periods. For near future (2020-2050) under SRES A2 scenario, out of 4 GCMs presented in the original paper, one indicates increase in runoff, both low flows and peak flows, one indicates a decrease in runoff (again throughout a range of flows), and two indicate relatively little change. Further into the future, however, the balanace shifts towards drier conditions. The mean discharge (mean of all monthly discharges at Mukwe) was projected to change in the range of +38% to -39% for 2020-2050, but within the range of -2% to -55% for 2070-2099. The mean minimum discharge (mean of minimum monthly discharges) was projected to change by +29% to -40% for 2020-2050 but -14% to -59% in 1070-2099,

The results by Wolski (2009), who utilized statistically downscaled data, suggested an overall increase in wetness of the Okavango system under future anthropogenically transformed climate, both during peak flows and low flow conditions, even for the “dry” scenario (Fig. 12).

In the Hughes et al. (2011) study, the main result was that for climate change associated with a 2 deg. Increase in mean global temperature, there is a considerable difference in impacts between the seven GCMs used in the analyses, and that these differences are larger in magnitude than the change signal obtained from the individual GCMs (Fig. 12). Two out of 7 GCMs produced increase in mean annual flows in the range of 15-30%, while five produced decreases in the range of 10-32% and one GCM produced conditions similar to these observed in the past. Additionally, two GCM produced shifts in the timing of peak flow, however, in opposite directions. In the remaining GCMs – timing of peak flows was not projected to change.

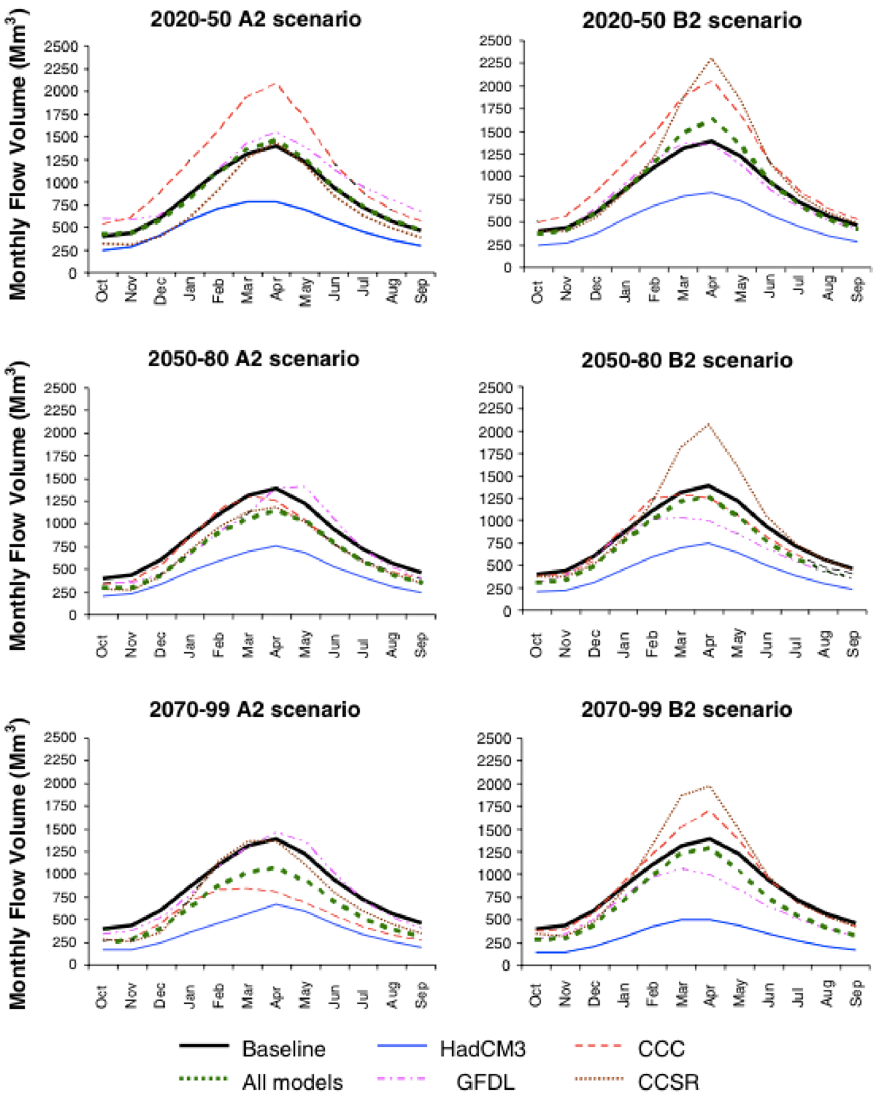


Fig. 11 Mean monthly discharges of Okavango River at Mukwe under future climate obtained within WERRD project (from Andersson et al. 2006).

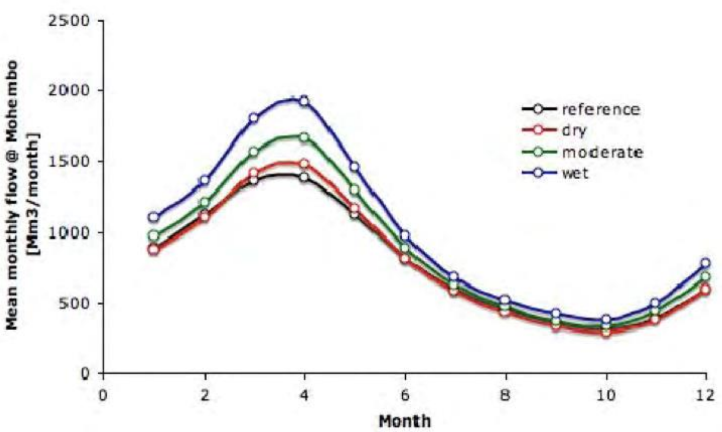


Fig. 12 Mean monthly Okavango River discharges at Mohembo under future climate simulated within TDA/EFA project (from Wolski, 2009).

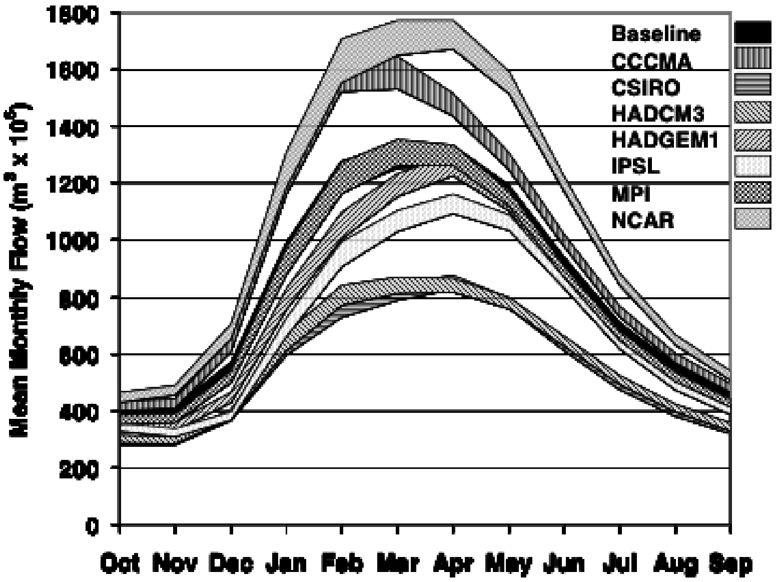


Fig. 13 Mean monthly discharges of Okavango River discharges under future climate corresponding to global warming of 2 degC, obtained within QUEST project (from Hughes et al., 2011).

Results of analyses of GCM rainfall and temperature trajectories in the 21st century that account for multidecadal fluctuations, obtained by Wolski et al. (2012) indicate that actually approximately 50 % of CMIP3 GCM realizations simulate increasing rainfall, while 50 % simulate decreasing rainfall, with the overall multimodel ensemble median not deviating strongly from the average long-term conditions (Fig. 14). Without detailed analyses it is difficult to ascertain the exact meaning of this result. However, a conjectural interpretation might be that the multi-model ensemble results indicate a lack of change in rainfall under changing climate (50-50 split of increase/decrease in model simulations is an expected result in such a situation.) On the other hand, there is a high degree of agreement between the members of the ensemble in terms of future trajectories of air temperature. Increasing temperature only will cause increase in evaporation and thus decrease in runoff and river discharges. The cumulative effect of these two is thus a widely spread range of possible future discharges with the drier conditions becoming progressively more likely in the future (Fig. 15). It is important to note that the individual MME members depicted in Fig. 14 and Fig. 15 represent possible trajectories of the future hydro-climatic system. It is uncertain which of these trajectories will the system’s one resemble. The MME median does not represent a more likely trajectory of river discharges, but rather indicates the central tendency of the entire ensemble, which should be interpreted in probabilistic terms.

In the context of multidecadal oscillations, the results indicate that their magnitude remain unchanged under projected climate (Fig. 16), with the oscillations superimposed on a general long-term trend. It is possible that the trend will be positive, i.e. towards an increase of overall wetness of the system, or null, i.e. the overall wetness of the system will not change. It is, however, more likely that the trend will be negative, i.e. towards the decreasing wetness of the system. This increase in probability of negative trend is attributed to the increase in temperature and thus PET rather than change in rainfall.

In spite of the simulation results reflecting the multidecadal oscillations directly, no conclusions could be drawn about timing of the wet and dry sequences in the future. This is because there was no coherence in timing of the multidecadal oscillations between the various GCM runs, not even between the different runs of an individual GCM. This indicates that the oscillations are not caused by external (solar) forcing (which is identical between all the GCMs). Rather the oscillations are caused by internal feedbacks in the atmosphere-ocean system. Because the various runs of GCMs are initiated from an arbitrary state of the system (the so called initial-condition ensemble), these feedbacks do not align between the runs.

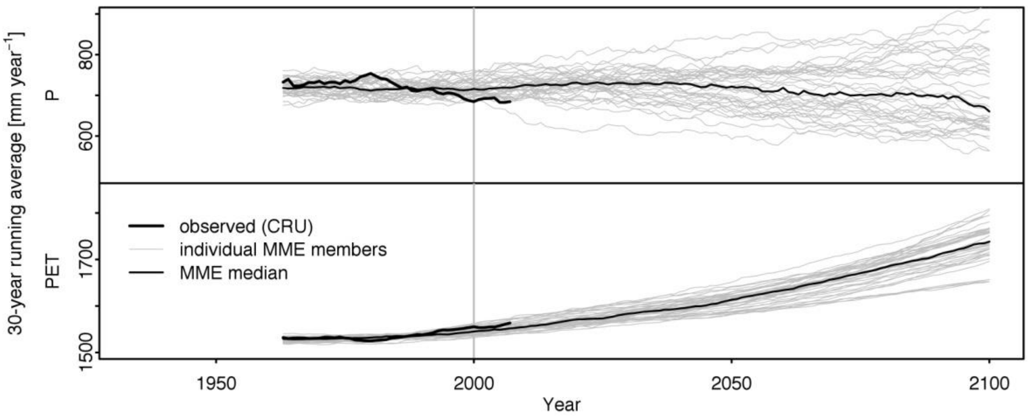


Fig. 14 Individual trajectories of 30-year running averages of rainfall and PET in the upper Okavango catchment, under past and future climate simulated by multi-model ensemble (MME) of 40 realizations with 18 GCM (from Wolski et al. 2012). The individual MME members represent possible trajectories of the future hydro-climatic system. It is uncertain which of these trajectories will the system's one resemble. The MME median does not represent a more likely trajectory of river discharges, but rather indicates the central tendency of the entire ensemble.

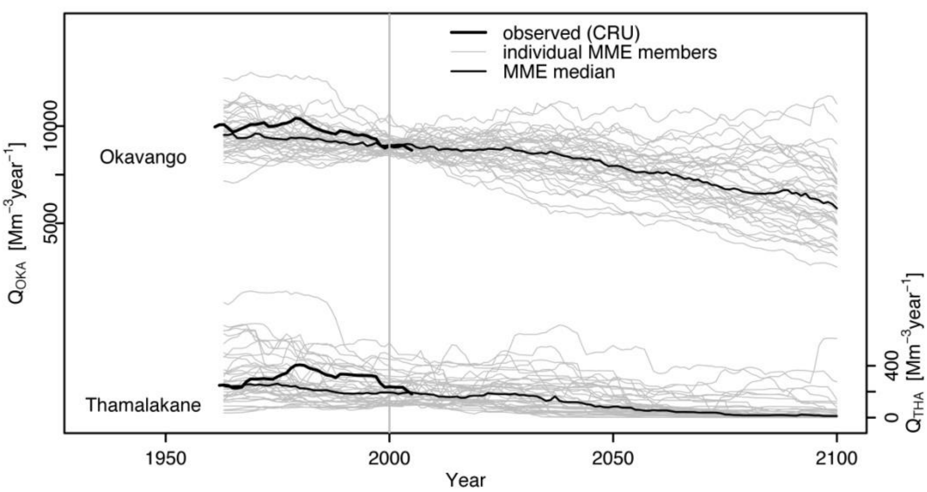


Fig. 15 Individual trajectories of 30-year running averages of Okavango River flows at Mohembo, and Thamalakane River flows at Maun, under past and future climate simulated by multi-model ensemble (MME) of 40 realizations with 18 GCM (from Wolski et al. 2012). The individual MME members represent possible trajectories of the future hydro-climatic system. It is uncertain which

of these trajectories will the real system's one resemble. The MME median does not represent a more likely trajectory of river discharges, but rather indicates the central tendency of the entire ensemble.

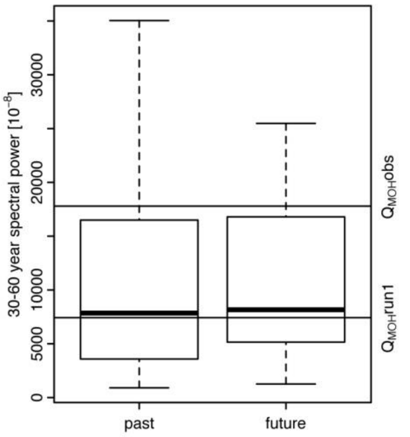


Fig. 16 Comparison of the role of oscillations of period > 30 years in GCM simulations for 20th (past) and 21st century (future) (from Wolski et al. 2012).

Impacts on the Okavango Delta

Climate change impacts on the Okavango Delta revealed in the dedicated studies are obviously conditional on the impacts on the Okavango River discharges, and subject to similar problems with differences between GCMs and differences between raw GCM data and downscaled GCM data.

The important messages derived from the climate change studies can be summarized as follows:

- Impacts on and transformation of hydro-ecological conditions resulting from anthropogenic climate change will be manifested throughout the Okavango Delta, not just in its peripheral part. This is because the Delta is characterized by a gradient of hydrological conditions (duration and frequency of inundation) extending from the inlet at Mohembo towards the periphery. This gradient underlies ecological functioning of the wetland, and any change of inflows or rainfall and temperatures over the entire wetland will have an impact along the entire gradient.
- The impacts will manifest in terms of change of location and acreage of various hydro-ecological units – there will be a shift of wetland classes towards Delta periphery under wetter scenarios, and their retreat towards Delta core under drier scenarios, with an opposite effect observed for dryland classes.
- The range of uncertainty in the magnitude of these impacts (as obtained from a number of GCM projections) is similar in magnitude to the transformation observed between the peak and troughs of the (natural) multidecadal oscillations in the system.
- The magnitude of multidecadal oscillations is projected not to change in the future, but these will be most likely superimposed on a trend. Although it is possible that the trend will be positive or null, it is more likely that the trend will be the drying one. This drying trend is attributed to increasing temperature and thus increasing

evaporation, effect of which is very significant in the Okavango Delta, where 98 % of water evaporates.

- The projections of multidecadal fluctuations should be interpreted as follows: there will be sequences of wet years and sequences of dry years in the future, similar to these observed in the past. However, progressively, the wet years will be less likely to be as wet as these in the past, and dry years will be more likely to be drier than these observed in the past.
- The consequences of the influence of increasing temperatures on the hydrological processes in the Okavango Delta will be strongly manifested in the conditions in the Delta terminal rivers: Boteti and Kunyere. The analyses project possible reduction in duration of flow into these rivers, even under the wet, downscaling-derived scenarios. However, put in the context of geomorphological processes taking place in the Okavango Delta, climate change induced effects can be exacerbated or moderated by shifts in distribution of flows in between the distributaries. Obviously, should such a new shift emerge – a gain of flows in one terminal river will be accompanied by a reduction in flow in another.

SUMMARY, MAJOR GAPS AND RECOMMENDATIONS

In summary, the results of climate change impact studies do not allow for determination of future conditions in the Okavango Basin with a high degree of confidence. Various methods and various subsets of available GCM projections suggest a range of possible conditions spanning both considerably wetter and considerably drier future conditions.

Importantly, it has to be noted that under the assumption of equiprobability of members of multi-model ensemble, future climates simulated by individual models are equally likely to occur. As a consequence the median or average of MME is as likely to represent future conditions as any of the members. Figures such as Fig. 11, Fig. 12, Fig. 13, Fig. 14, Fig. 15 and Fig. 16 **must not** be interpreted in terms of median of individual simulations as an indicator of projected change. Rather, the median should be used to indicate the change in **probability of future conditions**. It is possible that extremely “wet” or extremely “dry” conditions depicted in any of these figures will actually occur. The change in the median of MME indicates whether those “wet” or “dry” are more or less likely.

The following general conclusions can be drawn from the studies analysed here:

- When GCM data are used directly (through the change factor method, or scaling approaches), there are a number of GCM models that suggest increased discharges in the future, both in terms of baseflows and peak flows. However, a larger number of GCM realizations suggest reduced discharges, both for baseflows and peak flows. These effects were observed in three relatively independent studies (Andersson et al. 2006, Hughes et al. 2011 and Wolski et al. 2012).

- These results are consistent with the results of simulation of future trajectories of rainfall, air temperature and river discharges with a multi-model ensemble of GCM realizations (Wolski et al. 2012). These indicate an increase in probability of drier conditions in the future, which is driven by change in temperature. Importantly, the simulations indicate that multidecadal-scale fluctuations are likely to be present in the future and that their magnitude of will likely be similar to that observed in the past.

- Increase in probability of wetter conditions in the Okavango basin were obtained only in the study where GCM data were statistically downscaled. This result is underlain by an increase in rainfall in the catchment that more than compensates the increase of evaporation related to the increase in temperature.

- In theory the downscaled simulations are more scientifically sound and defensible than the studies based on direct use of GCM data. However, the lack of general agreement between the downscaling results and the results of several studies based on direct use of GCM data suggest the need to investigate climate change signal with another dowscaling method before unconditionally accepting the current downscaling results.

- The analyses of the observed past trends in the region's climate and system's hydrological responses do not contribute any information assisting in determination of future changes, as these are dominated by the effects of multidecadal oscillatory variability.

- The results of climate change attribution study for the 2009-2011 floods (Wolski et al. submitted) indicate, however, that probability of events of the magnitude observed in 2009-2011 has decreased under current climate as compared to the pre-industrial climate. The 2009-2011 events were large **in spite** of the anthropogenic climate change and not due to it. These events were likely driven by processes in the global climate system that underlie the multidecadal variability in the Okavango, and which are likely to be relatively uninfluenced by the anthropogenic climate change.

In view of the above, at this stage it is not possible to confidently determine the direction of change in local climate and hydrological responses, let alone quantify expected mean and uncertainty band around it. In order to achieve that, a comprehensive comparative study based on multi-method dowscaling analyses is needed to contextualize the somewhat controversial results of Wolski (2009) study.

There are two important current developments in the climate change science that may assist in this task:

1) CMIP5 data archive, which a repository of GCM simulations feeding into the forthcoming 5thth Assessment Report, is currently fully populated. The models included in the archive represent current status of climate modelling and have improved spatial resolution and process representation compared to CMIP3 models. It is imperative that a reassessment of climate change impacts for the Okavango is made using projections generated by these models.
2) CORDEX data (http://wcrp.ipsl.jussieu.fr/SF_RCD_CORDEX.html) are soon coming online. CORDEX will include a systematic set of dynamically downscaled projections, using a variety of methods. This is certainly an opportunity to resolve the downscaling-raw GCM discrepancy revealed in the earlier work in the Okavango. The TFO study, which is utilizes CORDEX data creates an opportunity to include additional source of information – RCM-based dynamical downscaling, although with a relatively low size of the ensemble (2 GCMs and 2 RCMs). An effort should be undertaken to expand the size of that ensemble.

REFERENCES

Alemaw B.F., 2009. Hydrological modelling and possible climate change impacts in a wetland system: the case of the Okavango Delta, Botswana. Improving Integrated Surface and Groundwater Resources Management in a Vulnerable and Changing World (Proc. of JS.3 at the Joint IAHS & IAH Convention, Hyderabad, India, September 2009). IAHS Publ. 330, 2009, 239-246.

Andersson L., Wilk J., Todd M.C., Hughes D.A., Earle A., Kniveton D., Layberry R., Savenije H.H.G., 2006. Impact of climate change and development scenarios on flow patterns in the Okavango River. Journal of Hydrology 331 (1–2), 43–57.

Bauer P., 2004. Flooding and salt transport in the Okavango Delta: key issues for sustainable wetland management. Diss. No. 15436, ETH Zürich, Switzerland

Brown C., 2011. Decision-scaling for Robust Planning and Policy under Climate Uncertainty. World Resources Report Uncertainty Series. Available at http://www.worldresourcesreport.org

Brown A., Gawith M., Lonsdale K. & Pringle P., 2011. Managing adaptation: linking theory and practice. UK Climate Impacts Programme, Oxford, UK.

Brown C., Wilby R.L., 2012. An Alternate Approach to Assessing Climate Risks, Eos Trans. AGU, 93(41), 401.

Hughes D.A., Kingston D.G. and Todd, M.C., 2011. Uncertainty in Water Resources Availability in the Okavango River Basin as a Result of Climate Change. Hydrology and Earth System Sciences, 15: 931-9417.

Hewitson B.C. and Crane R.G., 2006. Consensus between GCM climate change projections with empirical downscaling: precipitation downscaling over South Africa. International Journal of Climatology, 26: 1315-1337.

IPCC, 2007. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, USA.

Jury M., 2010. Climate and Weather Factors Modulating River Flows in Southern Angola. Int. J. Climatology, 30(6): 901-908.

Jury M., 2012. A return to wet conditions over Africa: 1995–2010 Theor Appl Climatol. DOI 10.1007/s00704-012-0677-z

Lempert R., Nakicenovic N., Sarewitz D., and Schlesinger M., 2004. Characterising climate change uncertainties for decision-makers. Climatic Change, 65:1–9.

McCarthy T.S., Green R.W., Franey N.J., 1993. The influence of neo-tectonics on water dispersal in the northeastern regions of the Okavango Swamps, Botswana. J Afr Earth Sci 17:23–32.

McCarthy J.M., Gumbricht T., McCarthy T., Frost P., Wessels K., Seidel F., 2003. Flooding patterns of the Okavango wetland in Botswana between 1972 and 2000. Ambio 32(7):453–457.

Milzow C., Burg V. and Kinzelbach W., 2010. Estimating future ecoregion distributions within the Okavango Delta Wetlands based on hydrological simulations and future climate and development scenarios, Journal of Hydrology 381 (2010) 89–100

Murray-Hudson M., Wolski P. and Ringrose S., 2006. Scenarios of the impact of local and upstream changes in climate and water use on hydro-ecology in the Okavango Delta, Botswana. Journal of Hydrology, 331, 73-84. DOI 10.1016/j.jhydrol.2006.04.041.

Prudhomme C., R.L. Wilby, S.Crooks, A.L. Kay, and N. S. Reynard, 2010. Scenario-neutral approach to climate change impact studies: application to flood risk, J. Hydrol., 390, 198–209, doi:10.1016/j.jhydrol.2010.06.043.

Ramberg L., Hancock P., Lindholm M., Meyer T., Ringrose S., Sliva J., Van As J., VanderPost C., 2006. Species diversity of the Okavango Delta, Botswana. Aquat Sci 68:310–337.

Scanagri, 2005. Analysis of Water Resources Scenarios, Hydrology and Water Resources, Okavango Delta Management Plan. Unpublished technical report.

Thomas D.S.G., Shaw P.A., 1991. The Kalahari environment. Cam- bridge University Press, Cambridge.

Todd M.C., Taylor R.G., Osborne T., Kingston D., Arnell N.W., and Gosling S.N., 2011. Quantifying the impact of climate change on water resources at the basin scale on five continents – a unified approach, Hydrol. Earth Syst. Sci., 7, 7485–7519, doi:10.5194/hessd-7-7485-2010.

UKCIP (United Kingdom Climate Impacts Programme), 2009. A local climate impacts profile: how to do an LCLIP. UKCIP, Oxford.

Weber, T., Haensler, A., Kriegsmann, A., Jacob, D. 2013. Regional dynamical downscaling of climate change information over the Okavango River Basin. Africa Climate Conference (ACC) 15-18 October 2013, Arusha, Tanzania.

Wolski P., Gumbricht T. & McCarthy T.S., 2002. Assessing Future Change In The Okavango Delta: The Use Of A Regression Model Of The Maximum Annual Flood In A Monte Carlo Simulation, paper at International Conference on Environmental Monitoring of Tropical and Subtropical Wetlands, Maun, Botswana, 4-8 December 2002.

Wolski P., Savenije H., Murray-Hudson M. and Gumbricht T. 2006. Modelling of the flooding in the Okavango Delta, Botswana, using a hybrid reservoir-GIS model. Journal of Hydrology, 331, 58-72. DOI 10.1016/j.jhydrol.2006.04.040.

Wolski P., Murray-Hudson M., 2008. “Alternative futures” of the Okavango Delta simulated by a suite of global climate and hydro-ecological models, Water SA Vol. 34 No. 5, 605-610. www.scielo.org.za/scielo.php?pid=S1816-79502008000500010&script=sci_arttext

Wolski P., 2009. Assessment of hydrological effects of climate change in the Okavango Basin. Transboundary Diagnostic Analyses. OKACOM Secretariat, Maun, Botswana.

Wolski P., 2012. Trends in water resources base in Okavango River basin, Cubango-Okavango River Basin Water Audit Project. Report to FAO. Maun, October 2012.

Wolski P., Todd M., Murray-Hudson M.A, and Tadross M., 2012. Multidecadal variability in hydro-climate of Okavango river system, southwest Africa, in the past and under changing climate. Journal of Hydrology, 475, 294–305.

Wolski P., Stone D., Tadross M., Wehner M, and Hewitson B.. Attribution of floods in the Okavango basin, Southern Africa. Submitted to Journal of Hydrology.